LOCALIZED EVALUATION OF INTERFACE BOND OF REBARS IN CONCRETE USING FOCUSED ULTRASONIC IMAGING

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by

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CERTIFICATE

This is to certify that the thesis entitled "**Localized Evaluation of Interface Bond of Rebars in Concrete using Focused Ultrasonic Imaging**" being submitted by Mr. **Surendra Beniwal** to the Indian Institute of Technology Delhi is a record of bonafide research work carried out by him under my supervision and guidance. The thesis work, in my opinion, has reached the standard, fulfilling the requirements for the award of **Doctor of Philosophy** degree.

The research report and results presented in this thesis have not been submitted, in part or full, to any University or Institute for the award of any degree or diploma.

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Abstract

Nondestructive evaluation is widely applied for quality evaluation of cast metals and inspection of composites and structural concrete. Concrete is a heterogeneous mass of stone aggregates, cement paste and embedded steel rebars. The condition of the bond between the rebar and the surrounding concrete is critical from the strength point of view of the structure. Casting of concrete is an on-site process and therefore the chances of occurrence of entrapped debonds around rebars are high, *e.g.* due to honeycombing, air pockets or foreign inclusions. Slippage between the rebar and the surrounding concrete may also occur during the service life of the structure due to impact and local material degradation. Therefore, the development of a nondestructive evaluation technique for the assessment of the bond condition of rebars is extremely important and is the primary objective of this thesis.

We have applied ultrasonic imaging techniques to assess the bond condition of rebars through numerical and experimental investigations, on cement mortar and concrete media. Ultrasound is particularly sensitive towards the existence of cracks and air-voids in concrete because of the significant mismatch between the acoustic impedances of air and concrete. High frequency ultrasound (higher than 100 kHz) has been used in this work to facilitate its interaction with the rebars, even though this is not common for inspection of concrete. The problem of scattering of the incident energy by the aggregates located in the travel path between the source and the rebar is overcome by using a focused field to insonify a region of interest surrounding the rebar. This results in good signal to noise ratio in the received signals, which are used to reconstruct images of the medium.

For the imaging part, two different algorithms namely the Synthetic Aperture Focusing Technique and the Reverse Time Migration have been explored in combination with incident focused ultrasound. The Synthetic Aperture Focusing Technique is in practice for nearly two decades for imaging of concrete, but the application of the Reverse Time Migration algorithm is rather new in the field of Civil Engineering. The images of concrete constructed by using both of these reconstruction algorithms are able to differentiate between the debonded and bonded condition of the rebars. Particularly, Reverse Time Migration generated the rebar images with superior resolution, due to which the bond condition of the rebars could be identified more easily. The computations related to the two dimensional simulations of elastic wave propagation and image reconstruction schemes are coded in the MATLAB platform by the author.

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Symbols

Symbol	Definition
a_j^i	Recorded signal corresponding to i-th source and j-th receiver
a	Major axis of ellipse
A	A-scan signal
c_y, c_x	Coordinates of center of ellipse
C	Cross-correlation function; Image intensity, CC mode waves
e	Dilatation; Ratio of minor to major axis of ellipse
$\boldsymbol{E}$	Position vector of Emitter/source
f	Frequency; Modified reflectivity
F	Impulse function
$\boldsymbol{F}$	Position vector of focus point
f_i	Body force per unit volume, in i-th direction
G	Green's function
$\hat{i}$, $\hat{j}$, $\hat{k}$	Unit vectors along the three Cartesian directions
I	Image intensity
L	Path length
m, n	Indices for pixel location corresponding to m-th row and n-th column
N	Number of points in the measurement aperture
$N_y \times N_x$	Size of the matrix
N_f	Number of elements with material property of fine aggregates
P	Total number of source-receiver pairs in the aperture
$\boldsymbol{r}$, $\boldsymbol{R}$	Position vector; position vector of receiver

$\boldsymbol{r}_0$, $\boldsymbol{R}_e$	Position vector of the source/ emitter/ point of excitation
$\boldsymbol{R}_r$	Position vector of the receiver
$\boldsymbol{r}'$, $\boldsymbol{R}_s$	Position vector of the scatterer
S	Image intensity, CS wave mode
S_M	Measurement surface
t	Time
T	Time of flight
$\mathbf{u}$	Displacement field
u_i	Particle displacement in i-th direction
V	Enclosed volume
V_c	Velocity of compressional wave
v_i	Particle velocity in i-th direction
V_f	Volume fraction of fine aggregates
V_s	Velocity of shear wave
x, y, z	Cartesian coordinates along the three directions
$\boldsymbol{X}$	Column vector
α	Weighing factor
γ	Reflectivity of the medium
δ	Perturbation
λ, μ	$Lam\acute{e}'s$ Parameters
μ	Mean value
θ	Orientation of major axis of ellipse
σ	Standard deviation
ρ	Density
ν	Poisson's ratio
ε_{ij}	Strain tensor
σ_{ij}	Stress tensor
$\boldsymbol{\omega}$	Rotation field
ϕ	Field quantity

ϕ_B	Scattered field
ϕ_{in}	Incident field
ϕ_o	Observed/measured field
∇	Nebla operator
∇^2	Laplacian, Laplace operator

Acronyms

Acronym	Definition
2D/3D	Two Dimensional/ Three Dimensional
C	Compressional wave mode
CC	Compressional incident, Compressional reflected wave
CS	Compressional incident, Shear reflected wave
FD	Finite Difference
FDTD	Finite Difference in Time Domain
FMC	Full Matrix Capture
GPR	Ground Penetrating Radar
IE	Impact Echo
NDE	Nondestructive Evaluation
PZT	Lead (Pb) Zirconium (Zr) Titanate (Ti) based Piezoelectric Transducer
ROI	Region of Interest surrounding the rebar
RTM	Reverse Time Migration
S	Shear wave mode
SAFT	Synthetic Aperture Focusing Technique
SAR	Synthetic Aperture Radar
TFM	Total Focusing Method
ToA	Time of Arrival
ToF	Time of Flight